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SIXTH QUARTERLY REPORT

PERIOD 1 OCTOBER – 31 DECEMBER 1963

RESEARCH AND DEVELOPMENT OF AN OPEN-CYCLE FUEL CELL SYSTEM

(NASA Contract No. NAS8–2696)

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Prepared for

George C. Marshall
Space Flight Center
Huntsville, Alabama

By

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ALLIS-CHALMERS
MILWAUKEE 1, WISCONSIN

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FOREWARD

This report was prepared by the Aerospace Power Systems Section, Research Division, Allis-Chalmers Manufacturing mfg. Company, Milwaukee, Wisconsin, under NASA Contract NAS8-2696. The work was administered under the direction of the Electrical Components and Power Supplies Section, Astrionics Division, NASA, Huntsville, Alabama. Mr. Richard Boehme is the technical supervisor for NASA.

This Sixth Quarterly Report covers the work completed from 1 October to 31 December 1963 and is submitted as per the 8 February 1963 Contract Modification.

Management direction at Allis-Chalmers includes Mr. Will Mitchell, Jr., Director of Research, and Dr. Powell Joyner, Mr. D. T. Scag and Mr. W. W. Edens, Assistant Directors of Research. The project is supervised by J. L. Platner, Manager and P. D. Hess, Chief Engineer. The Project Leader is D. P. Ghere.

The report was written by J. Euclide, R. Opperthauser, C. Pax, D. Ghere, and B. Nichols. 31 Jan. 1964 28p refs

ABSTRACT

Final tests of the Dynamic Vapor Pressure Control Breadboard System are described. A

Studies of the mechanisms of the Static Vapor Pressure Control System using a gas chromatograph and a mathematical model are discussed.

Included is a report of tests conducted to improve life and performance characteristics of the fuel cell. Operation of fuel cells electrically connected in parallel is discussed.

A description of a thermal mockup of a gas cooled fuel cell system is included. A 1500 watt developmental fuel cell system using Static Vapor Pressure Control will be built under this contract.

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1.0 SUMMARY

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Tests of the Dynamic Vapor Pressure Control System were concluded due to revision of the contract.

A program for studying Static Vapor Pressure Control has been outlined. This includes a computerized mathematical model to be verified by experimental studies using a gas chromatograph.

Fuel cells constructed with thinner electrolyte vehicles have shown improved performance characteristics. Cells constructed with a new combination of electrodes are showing excellent life characteristics, although the initial output is slightly lower than cells constructed with previous electrode combinations.

Operation of units made up of a number of single cells connected in parallel has been proven feasible. The parallel connected cells produce current in proportion to their ability.

A thermal mockup of a gas cooling system has been designed and is under construction. Data acquired from tests on this unit will be used in design of a cooling system for a 1500 watt fuel cell system.

AUTHOR

2.0 INTRODUCTION

During the past quarter a revision to this contract has been negotiated which redirects the research and development effort into the new method of moisture control called Static Vapor Pressure Control. The theory of operation of this control system and a discussion of initial feasibility tests are contained in the quarterly reports of Contract No. NAS8-5392. In view of the revised work scope of this contract, the tests of the Dynamic Vapor Pressure Control breadboard system were concluded. A new program has been planned and work has commenced in some areas. Plans for the next quarter and results of work during the past quarter are discussed in this report.

3.0 DYNAMIC VAPOR PRESSURE CONTROL - BREADBOARD SYSTEM

Testing of the Dynamic Vapor Pressure Control System, Figure 1, which was breadboarded with a seven-cell, 225 watt module, was suspended after completion of the last planned series of tests on the breadboard model. Operation of the system is summarized on Figure 2. The water removal curves on Figure 2 illustrate the operation and response of the moisture removal system incorporating the static condenser-separator.

Response to load changes and system startup was good. Despite slightly erratic operation of the bottom cell, as noted in the Fifth Quarterly Report, the total module voltage was satisfactorily maintained. The cell temperature and the temperature of the hydrogen leaving the condenser (T7), which are the two temperatures which must be controlled, were held within $\pm$ 3° C except during periods of startup, with no adjustment of controls. The mixing valve performance is best illustrated by the uniformity of temperature T7 when the temperature of the coolant into the cold port (T3) was allowed to rise to 70° C and then drop to 17° C. The effect on T7 was negligible. Since the breadboard system operated satisfactorily at rated load (40 amperes at 5.6 volts) and any improvements in the system would necessitate major alterations, the testing was suspended on October 17, 1963, due to the anticipated contract revision.

4.0 STATIC VAPOR PRESSURE CONTROL STUDIES

In order to acquire a more exact knowledge of the mechanisms of the Static Vapor Pressure Control System and to be able to predict the operation mathematically, a combined theoretical and experimental program has been initiated. A mathematical model will be programmed for computer solution. This solution will be verified and corrected by experimental data acquired from chromatograph tests of cells operating with Static Vapor Pressure Control.

The chromatograph test setup will be the same as that used during feasibility tests under Contract No. NAS8-5392 except that the setup was expanded to permit sampling from a greater number of locations within a cell. During the feasibility studies, it was discovered that under some conditions the vapor pressure was not uniform across the face of the cell. The revised setup will enable samples to be extracted from a number of locations in the interior of the cell on both the hydrogen and oxygen sides. The system revision and recalibration have been completed. A technique for extracting the samples from the interior of the cell has been developed and the initial tests have proven satisfactory. The test program is scheduled to begin early in the next quarter. Programming of the mathematical model for computer solution has started.

5.0 CELL IMPROVEMENT TESTS

A test program has been initiated to study and improve the performance, life and reliability of the Static Vapor Pressure Controlled fuel cell. This program will evaluate electrodes, electrolyte vehicles, and various configurations of electrode holders.

5.1 Electrolyte Vehicle Tests

To improve the fuel cell performance, electrolyte vehicles thinner than the standard 30 mil capillary membranes are being investigated. The improved performance is believed to be a result of a lower internal electrical resistance and a reduction in the gradient of the electrolyte concentration across the cell.

Performance tests have been completed on electrolyte vehicles of 10, 15 and 20 mil in thickness. Figures 3 and 4 illustrate the relative increase in output obtained by decreasing the thickness, in cells constructed with two different electrode pairs. The increase in current density at a constant voltage as the thickness decreases is particularly striking. The following table of data taken from the curves illustrates this for a case where the cell voltage is taken at 0.8 volts.

Electrolyte Vehicle Thickness (mils)	Current Density (ma/cm^2)	Current Density % of Standard 30 mil Thickness
Type A cell - 0.8 volts		
10	500	222
15	370	164
20	310	138
30 (standard)	225	100
Type B cell - 0.8 volts		
10	345	203
15	275	162
20	215	126
30 (standard)	170	100

These tests were run on cells of standard construction, except as noted, and with an active area of 172 cm^2. While the actual numerical values on these curves may change as improvements in the cells are made, the curves provide a valuable reference for the relative voltages which can be expected as the electrolyte vehicle thickness is changed.

Measurements of capillary potential are being conducted with the various thicknesses of asbestos in question. The capillary potential, which represents the pressure differential across the membrane which will force liquid (KOH) from the largest pores of the membrane, is an important factor in choosing the electrolyte vehicle.

It appears from the data obtained so far that improvements in fuel cell performance can be obtained by reducing the thickness of the electrolyte vehicle, while still maintaining adequate tolerance to reactant pressure differentials.

5.2 Life Tests

As rated current densities have increased, it has been noted that the output of previous cells gradually decreased with time even though all other operating conditions were held constant. In order to get uniform output for extended periods of operation at high current densities, several cells constructed with new combinations of electrodes were tested. One of these cells, Type "B" mentioned previously is exhibiting excellent life characteristics. The initial performance of this cell was lower than Type "A". However, the performance has remained extremely stable.

The first Type B cell was constructed with a 30 mil electrolyte vehicle and had an initial output of 162 ma/cm^2 at 0.8 V. This cell is still operating at 1,942 hours of operation at a current density of 162 ma/cm^2 (28 amps) with less than 3% decline in voltage at this load. The operating temperature and pressure have been maintained at 88° C and 2.5 atmospheres throughout the test. Figure 5 shows the volt-amp characteristics (on an expanded scale for clarity) after one, 500 and 1000 hours of operation at 162 ma/cm^2.

In order to determine the repeatability of the above test, a duplicate cell has been constructed. This second cell has operated under identical conditions of temperature, pressure and load, for over 400 hours with no detectable decline in voltage to date. The initial voltage was within 1/2% of the initial voltage of the original cell.

Another cell is being tested to determine the effect of higher current densities of the same Type B construction. This cell used a thinner electrolyte vehicle (.010") and operated at a slightly higher temperature (93° C). Other operating conditions and construction features were the same as the other two cells. This cell was operated for 1,163 hours at a current density of 215 ma/cm^2 (37 amps) with a voltage drop of about 2%.

5.3 Half-Cell Tests

A test bench has been constructed to facilitate testing of the half-cell potentials of various electrodes and cell constructions. Total voltage, cathode potential, anode potential and internal resistance can be measured with this setup which should provide valuable data for improvement of cell performance. The effects of changes in electrodes, electrolyte, electrolyte vehicle and operating conditions will be observed.

6.0 SERIES-PARALLEL FUEL CELL OPERATION

In an operating fuel cell module, it is not uncommon for some cells to be slightly stronger than others. If two or more single cells were connected in parallel, the stronger cells would, in effect, support the weaker ones by assuming a greater load. A number of these parallel connected sub-modules could then be connected in series to produce the desired total voltage. In addition to the resultant improvement in system reliability, several advantages for fabrication and assembly can be realized by series-parallel construction.

Load sharing studies on a four-cell module electrically connected in parallel, as shown in Figure 6, indicate that the fuel cells in a parallel stack share the current demand in proportion to their ability to meet a common voltage. That is, for a given current demand the cells adjust their individual current output until a common voltage is reached. No circulating currents between the cells were apparent. These studies were conducted over a range of loading with cell performance at various levels of depreciation. As an extreme, tests were conducted with the hydrogen gas flow completely blocked from one cell to determine if any current would pass through the cell due to the voltage produced by the other cells. The cell with the gas flow closed would not supply a current large enough to be detected by a milliammeter. When this cell was placed in parallel with the three other cells on open circuit of 1.05 volts, a circulating current of approximately 30 milliamperes was observed passing through the dead cell. This current decreased as the parallel stack was loaded since the common voltage decreased. At a current load of 120 amperes, the circulating current through the dead cell was approximately 20 milliamps, or less than 0.02 percent of the current output.

In a continuation of this test, a power supply was connected in series with the module and adjusted to deliver six volts at 100 amperes. This would simulate several modules in series with the test module. As expected no change in the current levels through the dead cell or change in the module voltage output was observed.

In order to force appreciable currents through a fuel cell with an external voltage source, electrolysis must occur. Electrolysis will only occur if the applied voltage is greater than 1.23 volts, the theoretical lower limit at which electrolysis occurs. Experiments indicate that the voltage necessary for electrolysis is, in practice, near 1.5 volts. A single hydrogen-oxygen fuel cell has a theoretical maximum open circuit voltage of 1.23 volts and a normal actual open circuit voltage of about 1.1 volts. Thus a fuel cell could not electrolyze water in a cell connected in parallel with it and no appreciable current could pass through a dead cell in a stack of parallel connected cells.

7.0 THERMAL DESIGN

Thermal control and waste heat disposal are necessary no matter which moisture control system is used. For this reason, the thermal design and cooling system studies have continued as before the contract revision except for a few changes to adapt to the Static Vapor Pressure Control System. As discussed in the last report, thermal design can be considered as being in two general areas:

(1) Thermal design of the cooling system
(2) Thermal design of the fuel cell module.

7.1 Thermal Design of Cooling System

Parts have been fabricated and assembly started on a thermal mockup of a gas cooled fuel cell system, Figure 7. The purpose of assembling this mockup is to prove the feasibility of a forced convection cooling system using a gas as the cooling fluid and to provide experimental data necessary for the design of such a system. In addition to this, the tests will provide information and experience with various components required for the system.

The mockup will consist basically of a simulated fuel cell module in a canister with fans recirculating the gas coolant over the cooling fins of the simulated module and through a heat exchanger. Heat will be transferred from the gas coolant to a primary liquid coolant in the heat exchanger. Necessary ducting and instrumentation will be included inside the canister. Heat input to the simulated fuel cell module can be varied to simulate the operation of a fuel cell module under various loads.

The instrumentation included will be selected to acquire design data in the following areas:

(1) Fan characteristics
(2) Parasitic Power
(3) Flow distribution

(4) Pressure drops
(5) Temperature profiles and control
(6) Cooling capacity

7.2 Thermal Design of Fuel Cell Module

In Section 3.2 of the Fifth Quarterly Report, the thermal design of fuel cell plates was discussed. Experimental measurements of temperature profiles within an operating cell have been performed to determine the validity of that analysis.

In the theoretical analysis, several simplifying assumptions were made. One of the assumptions was that heat loss along the axis of a module, or perpendicular to the individual plates, is negligible. In order to accomplish this in the fuel cell test module, the end plates were fabricated of a heavy phenolic material. These end plates reduced the heat loss to about 0.25% of that for magnesium end plates. In addition, the test cell was the center cell of five cells, which further reduced heat flow in the axial direction and more nearly simulated the thermal conditions within a cell in a module comprised of a large number of cells. A total of 24 thermocouples were placed in the cell as illustrated in Figure 8. Additional thermocouples monitored the temperature at an outside corner of each cell and the temperature of the center of the phenolic end plates. The measurements from these thermocouples confirmed that heat loss through these end plates was very small and could be considered negligible.

Another assumption made in the analysis was that there was a negligible temperature difference between the hydrogen and oxygen sides of a cell at any point. This test showed that this assumption can be considered true for design purposes. The temperature difference between a thermocouple on the oxygen side of the fuel cell and one directly opposing it on the hydrogen side was found to be less than 1° C at loads up to 175 ma/cm^2 (30 amps). Loads above this level would have required a cooling system with greater heat transfer rates than the natural convection cooling used for the test.

Another assumption in the analysis was that heat flux from the two finned sides of the plates was uniform and no heat was transferred from the reactant manifold sides of the cell. This assumption was not closely approached in the experimental setup. The temperature profile measurements showed a substantial heat loss through the manifold ends of the cell. This was due to the method of cooling used in the experimental setup and does not invalidate the assumption for a system using a complete cooling system. The temperature profile of the portion of the cell midway between the manifold ends was least affected by these end losses. The temperature differences measured between positions in this portion of the cell were within 0. 5° C of the predicted values.

The effect of Static Vapor Pressure Control System on heat removal was illustrated during these tests. With the moisture removal system operating normally, the temperatures would be very uniform and stable. If the shutoff valve for the water removal system was then closed, the temperatures throughout the cell would rise about 4 - 5° C within 30 seconds and then stabilize at this level or climb very gradually until the water removal system was placed back into operation.

In summary it can be concluded that two assumptions in the theoretical analysis were verified and can be considered correct for design purposes.

(1) Heat loss perpendicular to the individual plates, or through the end plates can be reduced to a negligible amount.

(2) Temperature differences between the hydrogen and oxygen sides of the cell are negligible for present operating current densities.

The assumptions that heat loss from the reactant manifold area was negligible and that heat flux from the finned area was uniform were not duplicated in the experimental setup due to the method of cooling used.

8.0 DEVELOPMENT MODEL

Under the new contract revision, a 1500 watt, 28 volt fuel cell system using Static Vapor Pressure Control is to be constructed. The construction will be in breadboard fashion but components will be aerospace oriented. Reactant supply, heat sink, instrumentation electric power and load may be supplied by laboratory facility. Voltage regulation will be 26 to 30 volts for load variations between 50% and 100% of rated load.

Design work has started on this unit. Most of the effort expended this quarter was in the design of the fuel cell module itself. Plates have been designed and fabrication of parts for a two-cell feasibility unit has started. Upon verification of the basic design, fabrication of components for the 1500 watt unit will commence.

During the next quarter, the cooling system will be designed and other system components selected and tested. Data and experience gained from the thermal mockup experiments will be used to continually upgrade the cooling system design.

9.0 FUTURE WORK

During the next quarter, the following work is planned:

(1) Commence Static Vapor Pressure Control chromatograph Studies (second series).

(2) Program mathematical model for computer solution.

(3) Continue cell improvement tests.

(4) Commence studies of half-cell potentials of operating fuel cells.

(5) Commence testing of thermal mockup.

(6) Assemble and check out development model fuel cell assembly.

(7) Initiate purge requirement testing.

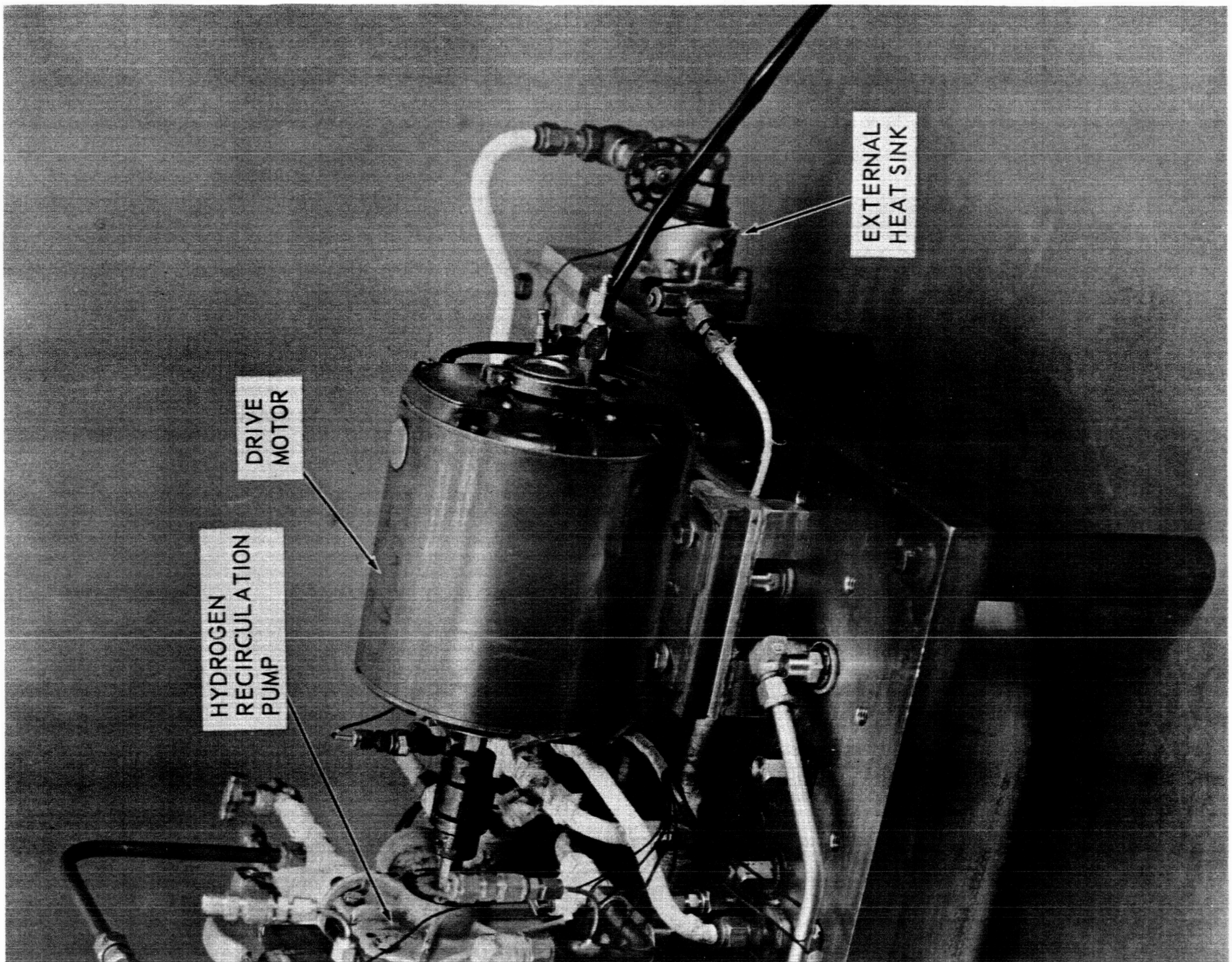
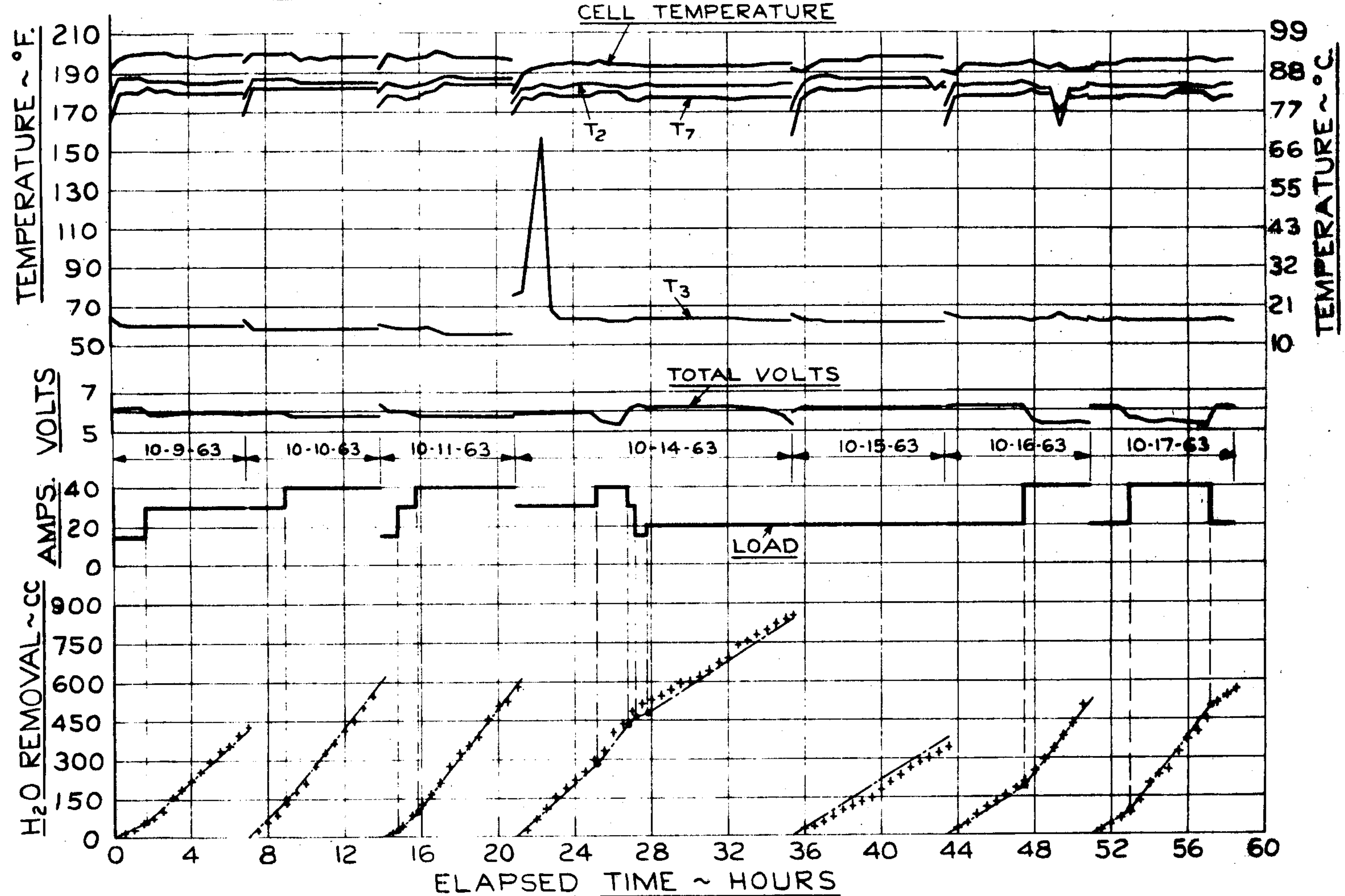


FIGURE 1

DYNAMIC VAPOR PRESSURE CONTROL
BREADBOARD SYSTEM

OPERATING DATA SUMMARY
FOR
DYNAMIC VAPOR PRESSURE CONTROL BREADBOARD SYSTEM



T_2 ~ COOLANT IN HOT PORT OF MIXING VALVE

T_3 ~ COOLANT IN COLD PORT OF MIXING VALVE

T_7 ~ H_2 OUT OF CONDENSER

—·—·— THEORETICAL H_2O REMOVAL

+ ACTUAL H_2O REMOVED

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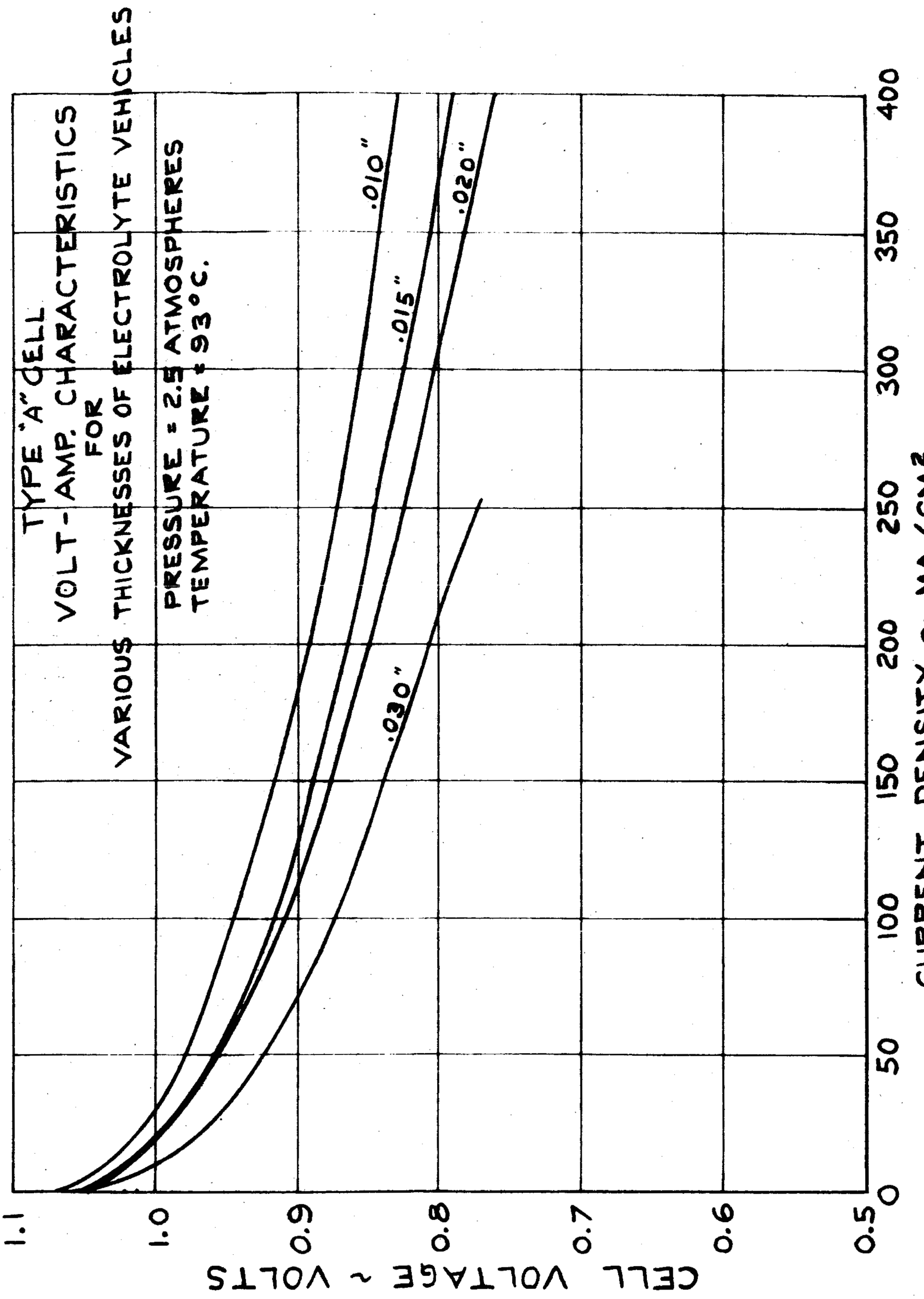
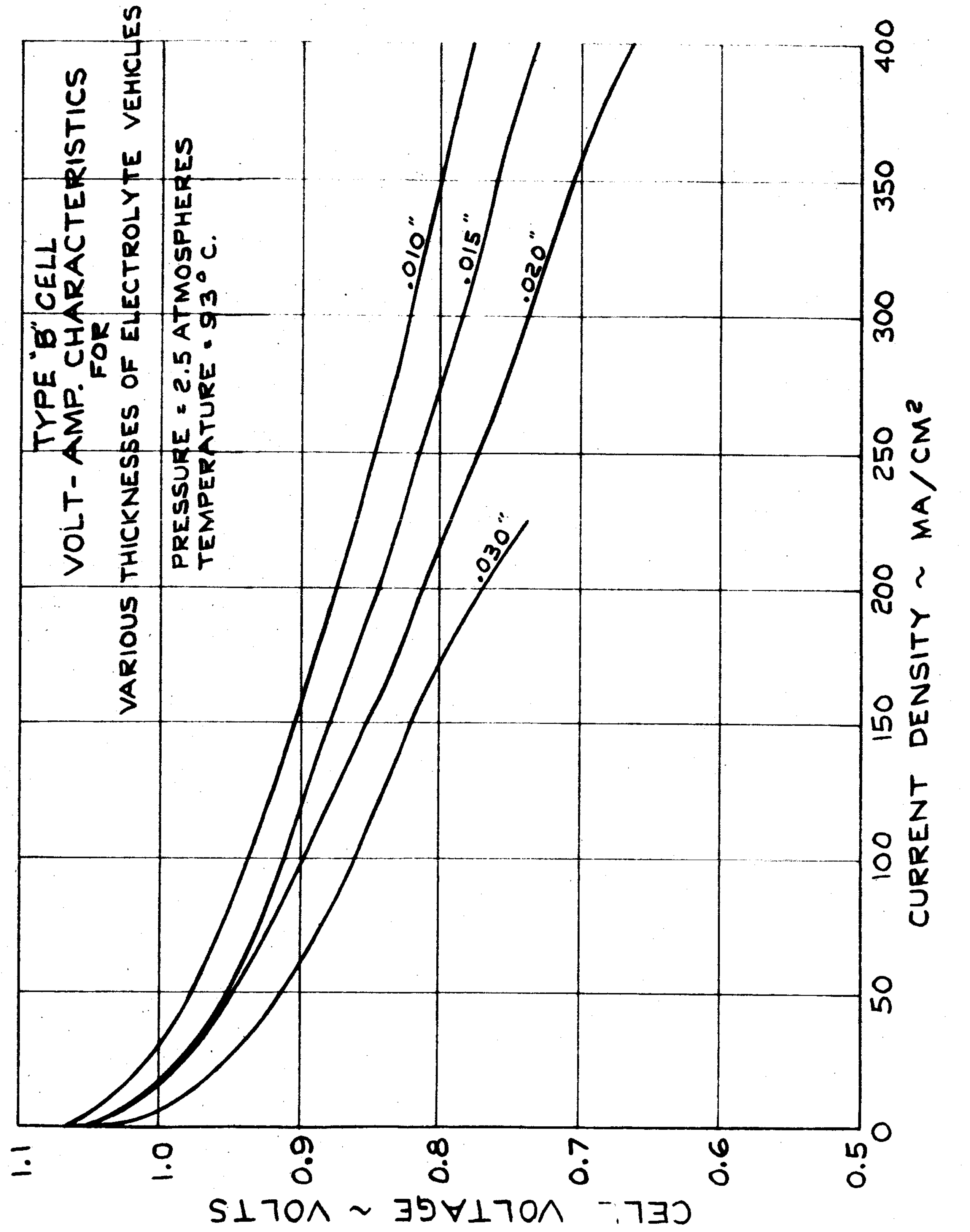
FIGURE No. 2

11-6-63



ALLIS-CHALMERS MFG. CO. FIG. No. 3 H.L.B. 12-9-63



ALLIS-CHALMERS MFG. CO. FIG. No. 4 H.I.B. 12-9-63

TYPE "B" CELL
LIFE TEST

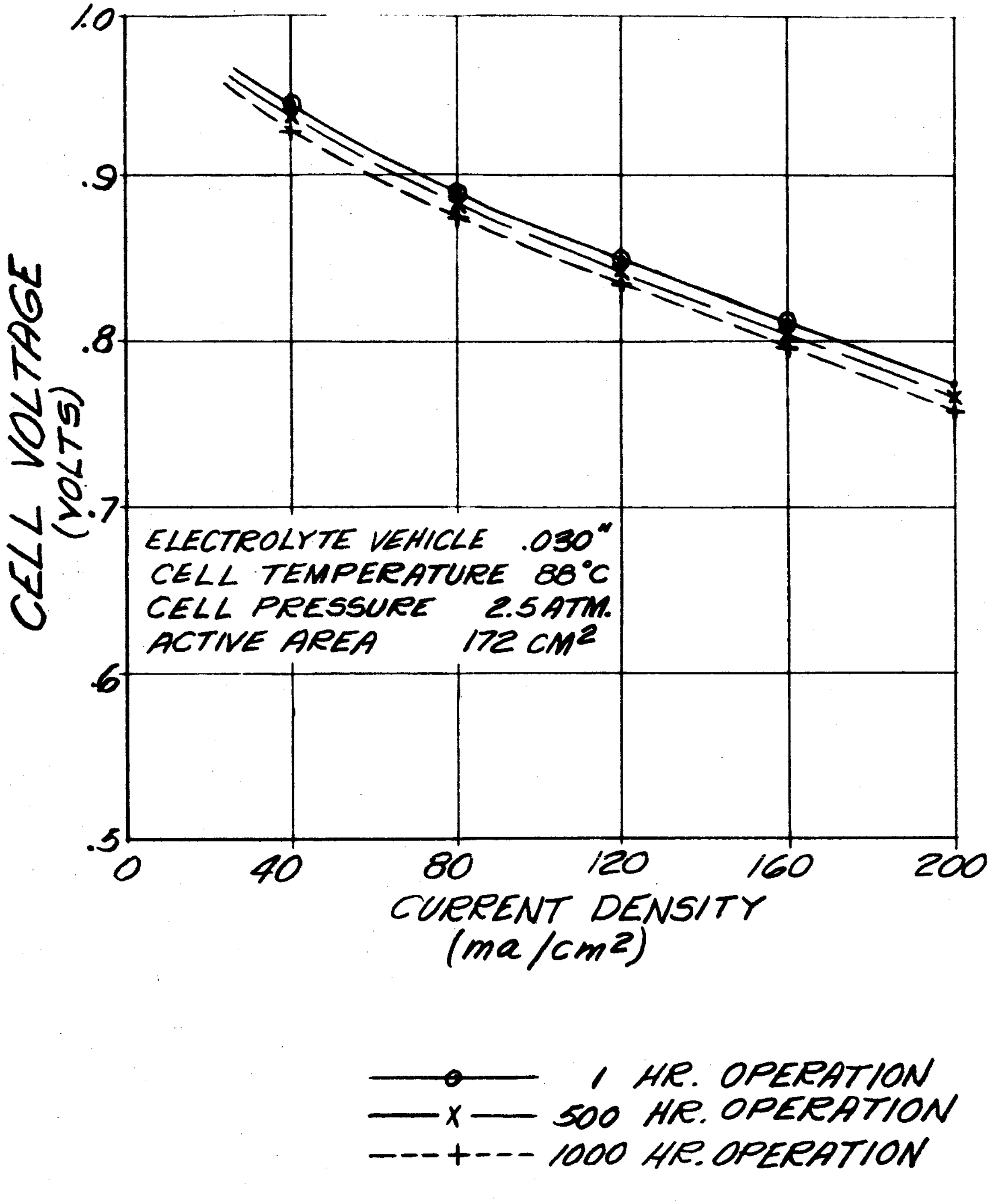
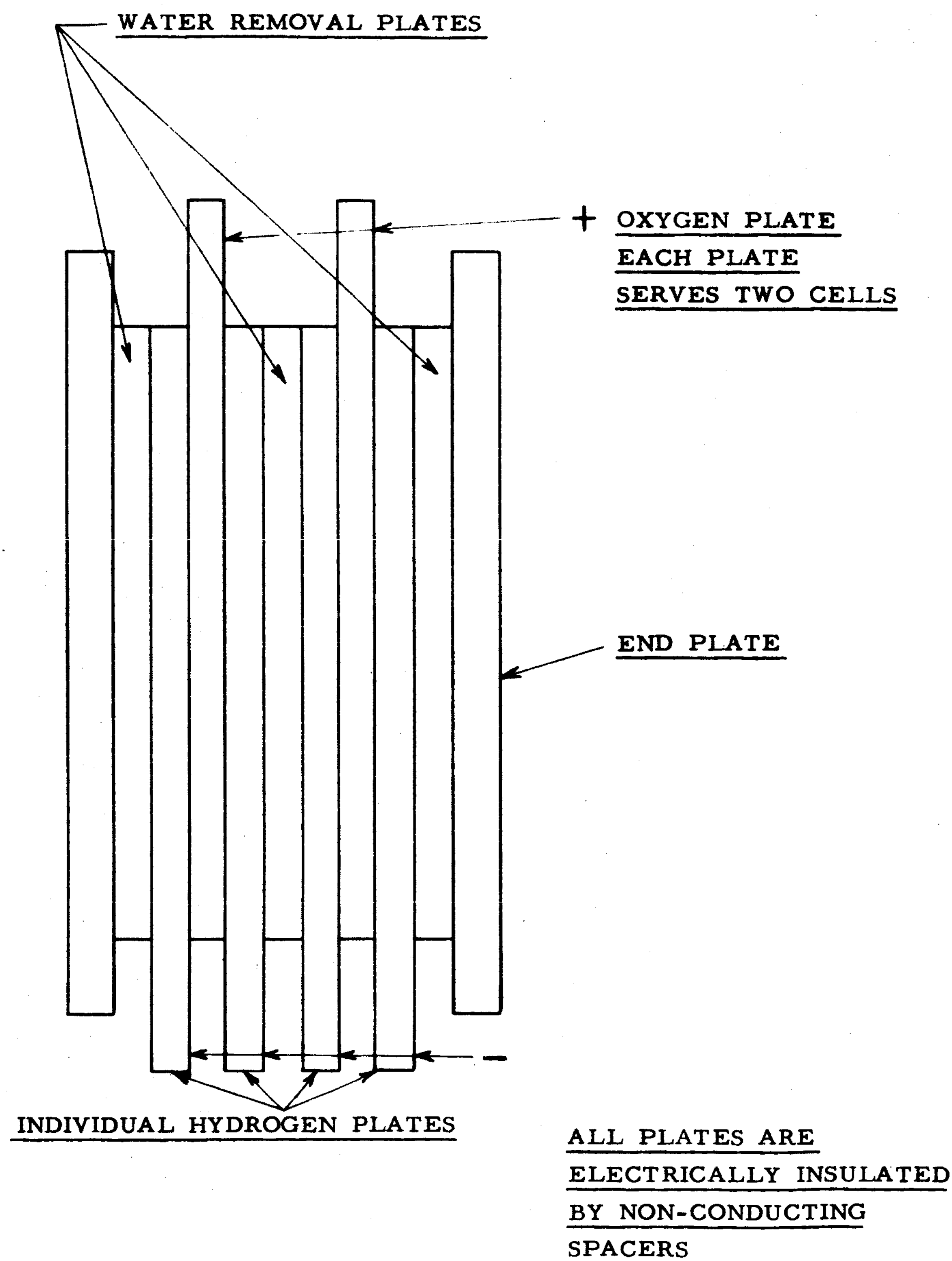


FIG. Nº 5



SCHEMATIC OF FOUR CELL PARALLEL TEST MODULE

FIGURE NO. 6

THERMAL MOCK-UP OF FUEL CELL SYSTEM WITH GAS COOLANT

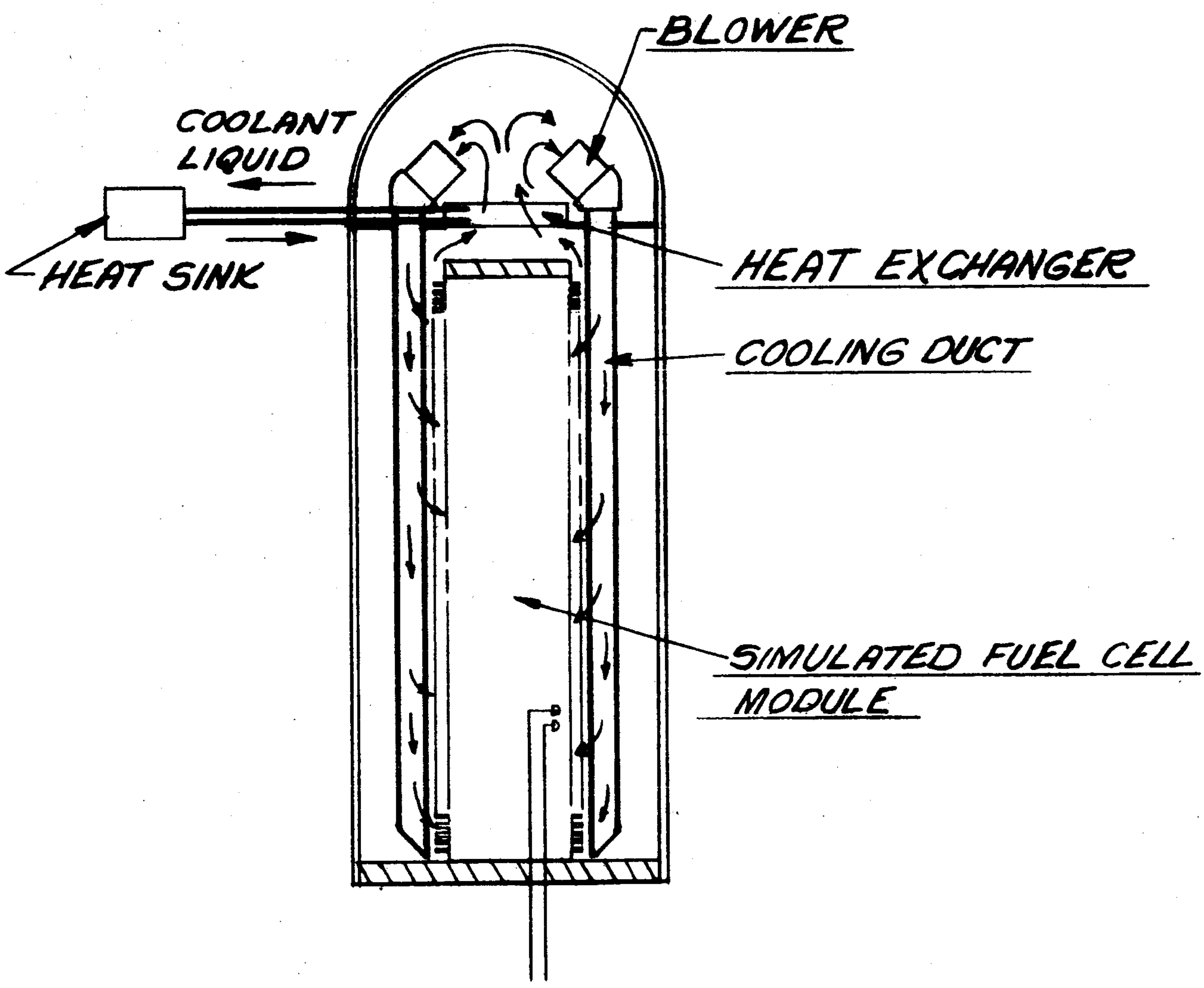


FIGURE Nº 7

FUEL CELL MODULE
FOR
THERMAL PROFILE TESTS

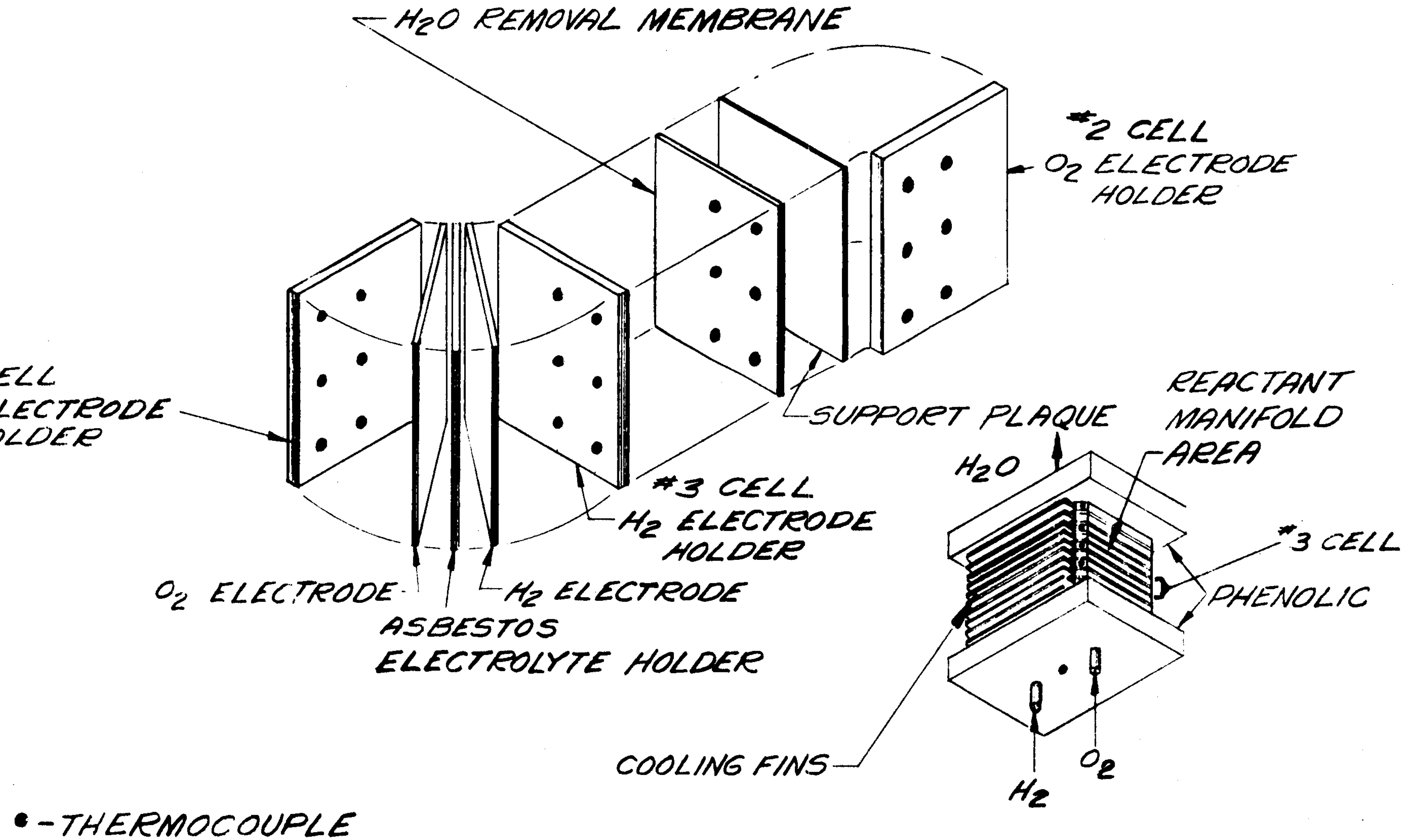


FIG. Nº 8